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TITLE: ASSESSMENT OF AVIONIC EQUIPMENT FIELD RELIABILITY AND MAINTAINABILITY AS FUNCTIONS OF UNIT COST

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I. INTRODUCTION

Pound-for-pound, avionics is generally recognized as the most expensive, complex and sophisticated part of an aircraft. In some modern aircraft, the avionics may cost as much as 30 percent of total flyaway cost, and avionic support costs for some older aircraft reportedly approach three-fourths of total support cost [1].[1]

Reliability and maintainability are critical characteristics that influence spares provisioning, maintenance resource requirements, system operational availability and, ultimately, investment and operating costs. Consequently, much attention has been focused upon improving the reliability and maintainability of avionics which, in the past, have been disappointingly low. Mr. Norman R. Augustine, a vice-president of Martin Marietta Aerospace, who served as Under Secretary of the Army and Assistant Director of Defense Research and Engineering in OSD, has reflected this disappointment in one of his published tongue-in-cheek "laws" based, in part, on an IDA study done in 1973. His law Number XIX states:

> If you are willing to spend enough money on an item of electronics, you can virtually guarantee that it cannot be made to work.

But perhaps things are not quite that bad.

The paper I am presenting, co-authored by Mr. Joseph W. Stahl and me, addresses avionics reliability and maintainability. The analysis was performed last year in partial response to a

[1] Numbers in brackets are keyed to the list of references at the end of this paper.

request of IDA by OASD (C^3I) to provide information for use by DSARC principals at the Full-Scale Development milestone. Since the 5000 series of DoD Directives and Instructions emphasize analytical comparisons of any new system under consideration by the DSARC with current, comparable systems,[1] we undertook analyses to determine if there may be one or more historical relationships between field reliability and maintainability and avionic equipment characteristics that would assist in forecasting those attributes.

The remainder of this paper is devoted to discussion of analyses and findings that:

- Suggest and exemplify methods for projecting field reliability and maintainability of avionic systems,
- Show predictive relationships between field reliability and avionic equipment unit cost, and maintainability and unit cost,
- Demonstrate that field reliability and maintainability vary with the level of technology incorporated in avionic equipment,
- Illustrate, by example, why the reliability of avionics in the field invariably has been lower than demonstration and qualification tests indicate.

II. THE DATA BASE

Our historical data base comprises the hardware unit costs and failure and maintenance data for each of 25 Air Force avionic equipments. The cost data are taken from a proprietary data base that represents the 100th unit cost, in FY 1978 dollars, of a number of avionic systems. The failure and maintenance data are from the Air Force Logistic Command's D056 Log reports for the six-month period August 1979 through January 1980 [2].

[1]Regarding reliability and maintainability, this requirement for comparisons with current, comparable systems is contained in paragraphs 16.a. and b., Encl. 4, DoDI 5000.2, March 19, 1980; paragraphs D.1.c.(2), and 2.a.(4) and 3.a.(2) (Encl. 3) DoDD 5000.39, January 17, 1980; and paragraph D.7b., DoDD 5000.40, July 8, 1980.

The cost data base identifies equipments as to hardware technology levels. The two most recent technologies are used in these analyses. The older of the two is identified as Solid State Devices (SSD) while the newer equipments are identified as Micro-Miniaturized and/or Complex Integrated Circuit Devices (MM). They range from low-cost automatic direction finders, radar altimeters and TACAN's, to high-cost radars, computer sets and ECM equipment. Dates of manufacture span the period 1965 to 1978.

The failure and maintenance data are for avionics included in the cost data base and installed in the following aircraft: F-4C, F-4D, F-4E, F-4G, RC-135A, C-130B, C-130E, F-15A, F-15C, C-141A, C-5A, F-111A and F-111E. Not every item of equipment was installed in every aircraft so, for the purpose of this study, where an item of equipment was installed in more than one aircraft, the totals of the reported operating hours,[1] failures, maintenance actions, etc., were computed.

III. FIELD RELIABILITY VS. UNIT COST

It is generally accepted that reliability and unit cost are functions of equipment complexity. If this is so, mean time between failures (MTBF) and unit cost may be assumed to exhibit reasonable correlation. It would follow that since failures generate maintenance actions, relatively good correlation might be expected between MTBF and MTBMA (mean time between maintenance actions) and between MTBMA and unit cost.

Table 1 presents the data used in this reliability analysis. The equipments are not identified so as not to disclose "privileged information."

[1]Time in use is presented in D056 reports as operating hours. D056 guidelines [3] prescribe that operating hours shall be computed by multipliers (factors) determined by the Item Managers and applied to reported flying hours. The guidelines acknowledge, however, that the ratio of operating timeto-flying hours normally is 1.00. D056 report data used in this study bear out the predominant use of 1.00.

Table 1. RELIABILITY AND COST DATA FOR SELECTED AVIONIC EQUIPMENTS

MICRO-MINIATURIZED AND/OR COMPLEX INTEGRATED CIRCUIT DEVICES				SOLID STATE DEVICES			
EQUIP. NO.	UNIT COST (FY-78$) 100th UNIT	MTBF (HOURS)	MTBMA (HOURS)	EQUIP. NO.	UNIT COST (FY-78$) 100th UNIT	MTBF (HOURS)	MTBMA (HOURS)
1	30,000	202.7	82.2	1	1,800	805.0	385.9
2	40,900	341.9	122.2	2	7,400	69.6	47.5
3	42,200	244.4	126.0	3	14,400	32.3	23.7
4	53,000	697.5	118.6	4	18,100	50.0	23.0
5	53,700	379.1	173.8	5	21,500	52.2	27.2
6	87,300	80.1	25.9	6	23,800	55.5	39.0
7	164,600	81.6	32.1	7	47,900	70.9	25.9
8	219,800	63.4	28.2	8	97,600	59.3	26.0
9	235,000	86.3	36.8	9	140,800	29.6	26.3
10	490,000	156.6	53.5	10	152,000	57.3	29.9
11	1,015,900	20.8	8.7	11	156,400	35.0	15.6
				12	338,600	6.5	2.9
				13	350,700	13.8	7.5
				14	498,200	13.8	8.0

The results of regression analysis,[1] using unit cost as the independent variable and MTBF as the dependent variable, are depicted in Figure 1. Examination of the plot leads to three interesting observations:

- Field reliability (MTBF) varies inversely with a power of the unit cost for Air Force avionic equipments of the same technology level. Reasonably good correlation is indicated, reinforcing the hypothesis that MTBF is a function of unit cost.
- Two distinct curves reflect the two technology levels represented in the data sample.
- The newer micro-miniaturized technology generally provides higher reliability for a given cost; roughly a factor of five over the older solid-state technology.

A similar regression analysis was performed using MTBMA as the dependent variable. Results are shown in Figure 2. Notably, the three observations made regarding MTBF versus unit cost can be made for MTBMA versus unit cost. The major differences between the MTBF equations and the MTBMA equations for the same technology level are the linear coefficients. The slopes of the equations are nearly the same. This suggests that for a given technology level, if one knows the MTBF or MTBMA, one can approximate the other based on the ratios of the linear coefficients.

The similarity of the MTBF-versus-unit-cost and MTBMA-versus-unit-cost relationships, coupled with reasonably good fits of the data points to the regression lines, prompted exploration of a direct relationship between MTBMA and MTBF. Figure 3, developed from data in Table 1, presents the results of regression analysis of MTBMA as a function of MTBF for all 25 equipments in the data base. The dependence of MTBMA upon

[1]The appendix comprises a discussion of the regression analyses performed in this study.

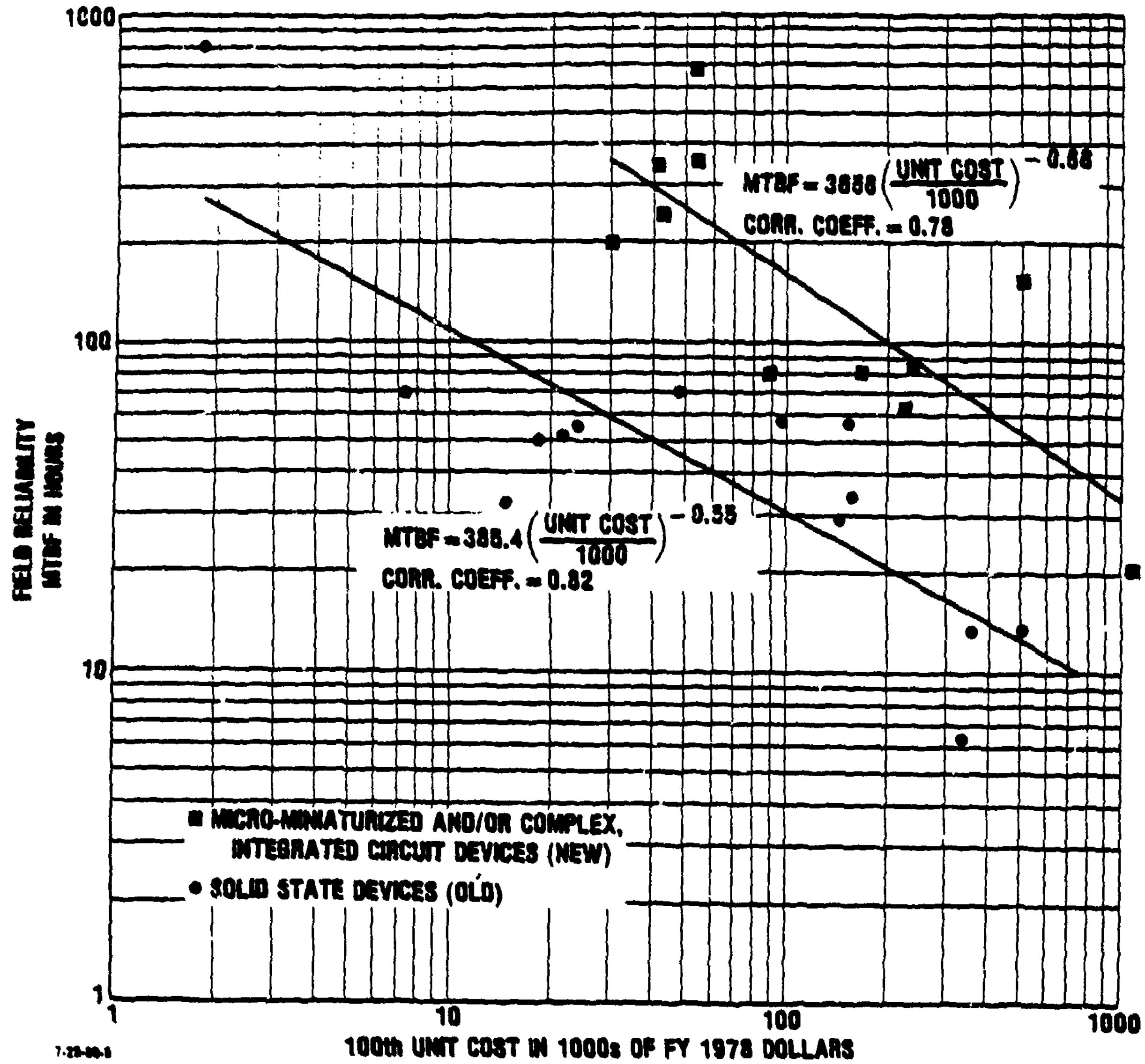

Figure 1. FIELD MTBF VERSUS UNIT COST FOR SELECTED AVIONIC EQUIPMENTS

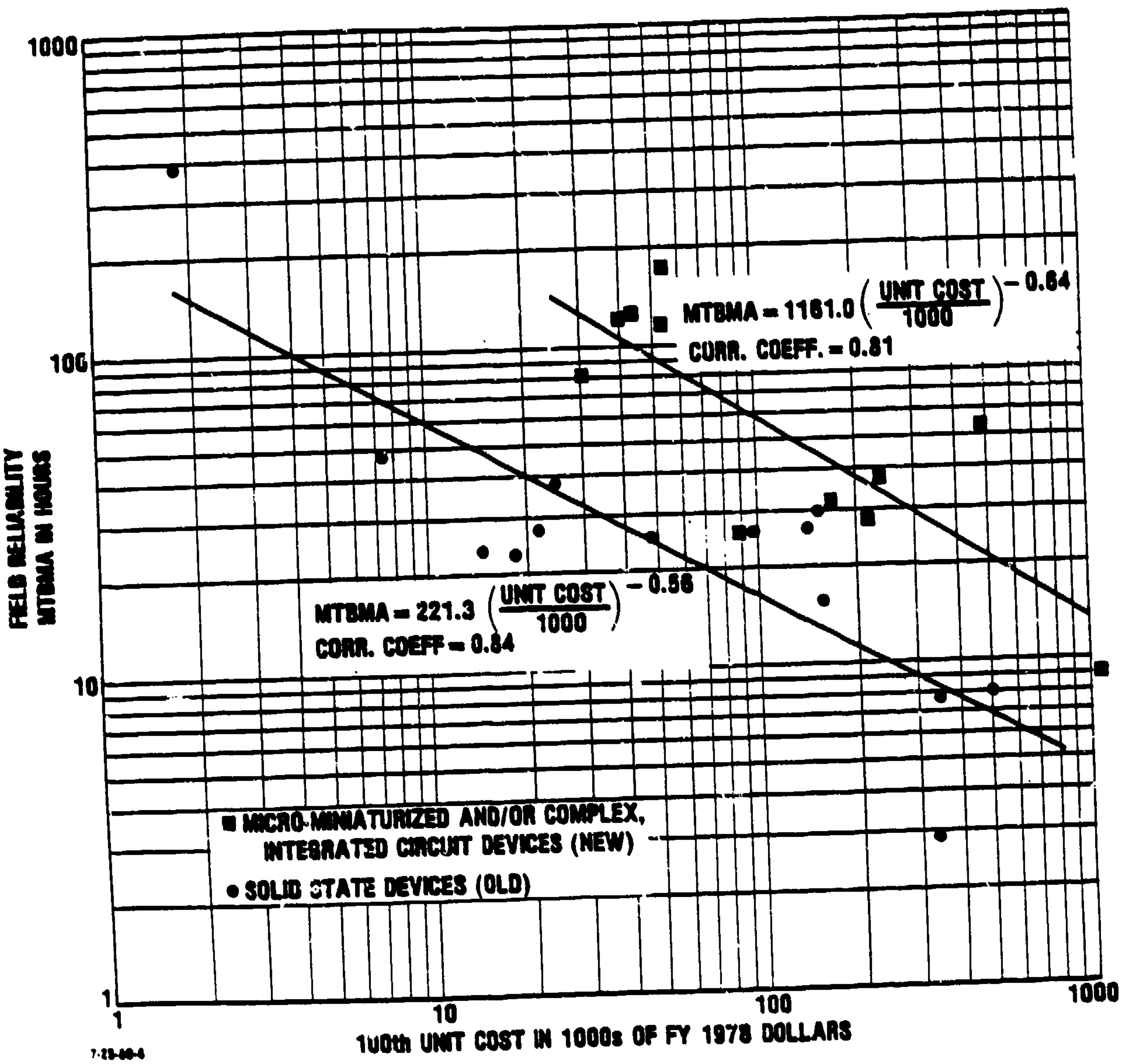

Figure 2. FIELD MTBMA VERSUS UNIT COST FOR SELECTED AVIONIC EQUIPMENTS

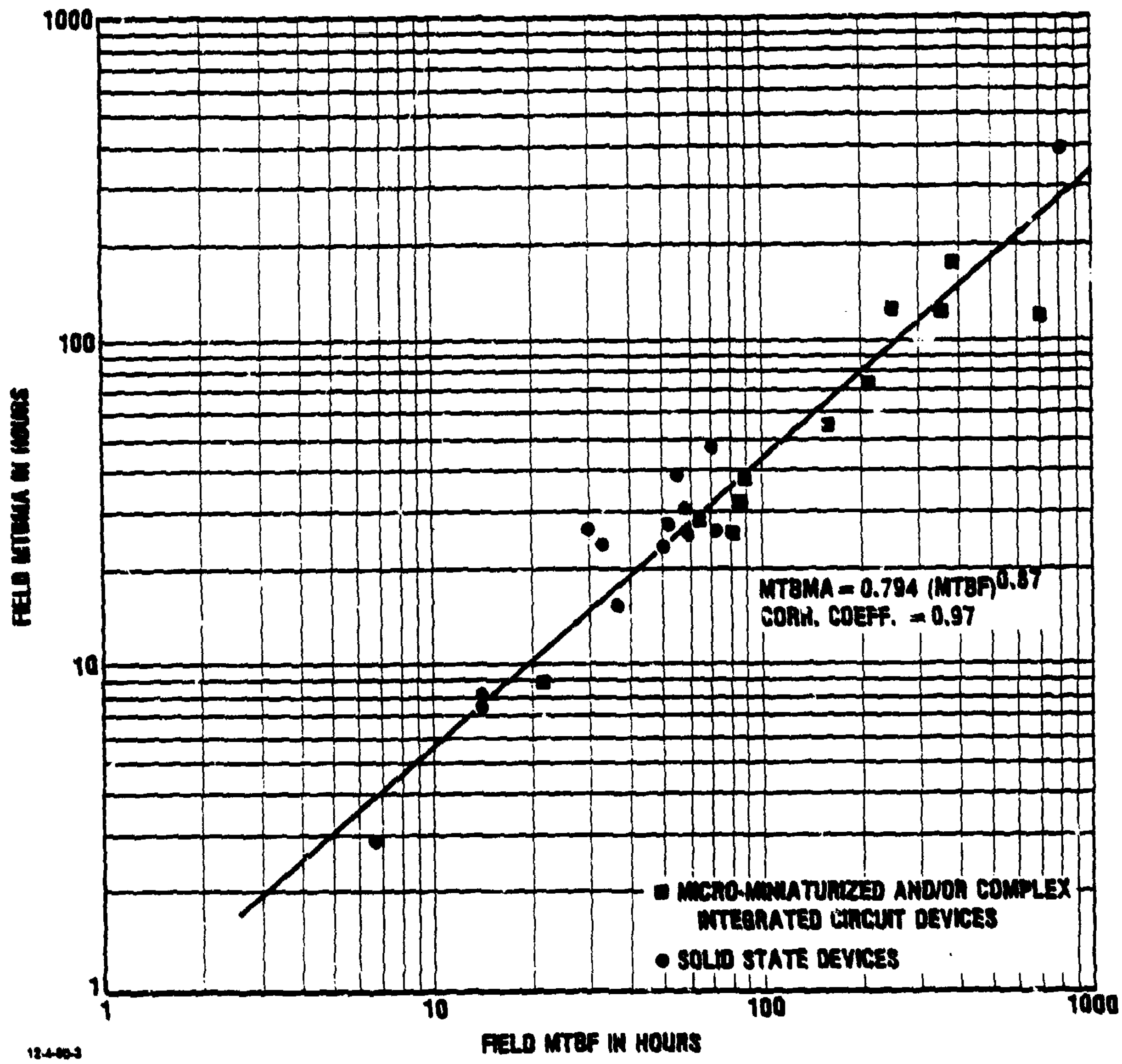

Figure 3. FIELD MTBMA VERSUS FIELD MTBF FOR SELECTED AVIONIC EQUIPMENTS

MTBF constitutes, a priori, a causal relationship. The degree of dependence, however, is conspicuous in that the strong relationship (r=0.97) appears to hold regardless of the technology level inherent in, or function of, the equipments.

IV. MAINTAINABILITY VS. UNIT COST

In addition to MTBF and MTBMA data, the D056 Log report contains maintenance man-hours for scheduled, unscheduled and shop maintenance actions at the organizational and intermediate (i.e., "shop") levels of maintenance.[1] This information enabled us to evaluate the maintainability specifications of an avionic system that was to be the subject of a DSARC decision.

The maintainability parameter stipulated in the System Segment Specification was mean corrective maintenance time (MCMT); coincidentally, at the organizational and intermediate levels of maintenance.[2] The MCMT values specified did not include maintenance set-up time, time to gain access to the equipment, nor time to complete reinstallation. The D056 Log report, however, does include those increments of time, making the man-hours shown in that report more representative of the maintenance effort that would be required in the field. We excluded scheduled man-hours given in the D056 Log report from our analyses because (a) the System Segment Specification prescribed that the equipment would not be subject to scheduled maintenance and (b) man-hours expended in scheduled maintenance are independent of failure occurrence.[3]

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[1]Unscheduled depot maintenance man-hours are not included in the D056 Log Report.

[2]Although the need for unscheduled depot maintenance was recognized in the Integrated Logistic Support Plan, MCMT at depot level was not addressed in the System Segment Specification.

[3]Inexplicably, programed (i.e., scheduled) depot-level man-hours are included in shop (i.e., intermediate-level) man-hours. The AFLC office responsible for the D056 Log Report [4] attributed less than five percent of reported shop man-hours to programed depot-level avionics (continued on next page)

Table 2 contains the data used for the maintainability analysis of the same equipments used in the reliability analyses: equipment failures, maintenance actions, unscheduled man-hours, shop man-hours and unit costs. This information constituted the data base to perform regression analysis using the two variables, unit cost and unscheduled-plus-shop-man-hours per failure. Figure 4 illustrates the results. The correlation coefficient and the scatter of points about the line representing solid state devices indicate somewhat questionable correlation between man-hours and unit cost. The equation generated by the micro-miniaturized data points yields such poor correlation ($r<0.25$) that it is not plotted. The scatter of the micro-miniaturized data points illustrates the independence of man-hours per failure and unit cost. In view of these results, the arithmetic means of man-hours per failure for both technologies are shown in Figure 4 as horizontal, dashed lines. They indicate that the average man-hours per failure for the micro-miniaturized equipments is about twice that of the older solid-state technology devices. This observation, coupled with the foregoing analysis of field reliability, suggests that although the equipments typified by the advanced technology fail less frequently, they require more man-hours per failure to repair.

Performing regression analysis using maintenance man-hours per maintenance action results in relatively poor correlations and relatively large dispersions of points about the regression lines in Figure 5. The arithmetic means, however, indicate that the more advanced micro-miniaturized equipments consume about one-third more man-hours per maintenance action at the organizational and intermediate levels of maintenance as do the older solid-state avionics.

(cont'd) maintenance. "Shop" man-hours in the D056 report include time spent on bench checks in which failures were reported but not verified. The same AFLC office advised that such instances account for about five percent of total report shop time. Although available information did not permit selective reductions in the D056 data, calculations revealed that the effects of relevant adjustments to the data would be trivial in the context of these analyses.

Table 2. MAINTENANCE AND COST DATA FOR SELECTED AVIONIC EQUIPMENTS

Equipment No.	Type[a]	No. of Failures	No. of Maintenance Actions	Man-Hours			Unscheduled + Shop M-Hrs. / Failure	Unscheduled + Shop M-Hrs. / Maint. Act.	Unit Cost (FY-78 $) 100th Unit
				Unscheduled	Shop	Unscheduled + Shop			
1	SSD	23	48	172	55	227	9.[illegible]	4.73	1,800
2	SSD	2,094	3,070	11,546	15,746	27,292	13.03	8.89	7,400
3	SSD	574	783	3,142	4,056	7,198	12.54	9.19	14,400
4	SSD	438	944	6,245	2,759	9,004	20.56	9.54	18,100
5	SSD	355	680	4,648	2,205	6,853	19.30	10.08	21,500
6	SSD	2,511	3,576	12,018	10,227	22,245	8.86	6.22	23,800
7	SSD	92	252	1,115	422	1,537	16.71	6.10	47,900
8	SSD	114	260	1,669	2,302	3,971	34.83	15.30	97,600
9	SSD	111	125	908	599	1,507	13.58	12.06	140,800
10	SSD	323	619	5,149	4,831	9,980	30.90	16.12	152,000
11	SSD	530	1,190	8,724	4,932	13,656	25.77	11.47	156,400
12	SSD	11,974	27,162	104,444	67,060	171,504	14.32	6.31	338,600
13	SSD	1,338	2,485	20,312	16,186	36,198	27.28	14.69	350,700
14	SSD	1,341	2,308	18,486	27,317	45,803	34.16	19.85	498,200
1	MM	258	636	4,272	7,176	11,448	44.37	18.00	30,000
2	MM	153	428	2,392	2,135	4,527	29.59	10.58	40,900
3	MM	214	415	2,147	3,181	5,328	24.90	12.84	42,200
4	MM	75	441	1,548	3,404	4,952	66.03	11.23	53,000
5	MM	138	301	1,705	2,732	4,437	32.15	14.74	53,700
6	MM	653	2,023	10,428	15,779	26,207	40.13	12.95	87,300
7	MM	641	1,632	8,899	17,375	26,274	40.99	16.10	164,600
8	MM	292	658	3,469	4,752	8,221	28.15	12.49	219,800
9	MM	606	1,420	7,482	14,364	21,846	36.05	15.38	235,000
10	MM	334	977	3,283	12,318	15,601	46.71	15.97	490,000
11	MM	2,520	5,982	45,471	77,714	123,185	48.88	20.59	1,015,900

[a] SSD = Solid State Devices
MM = Micro-Miniaturized and/or Complex, Integrated Circuit Devices

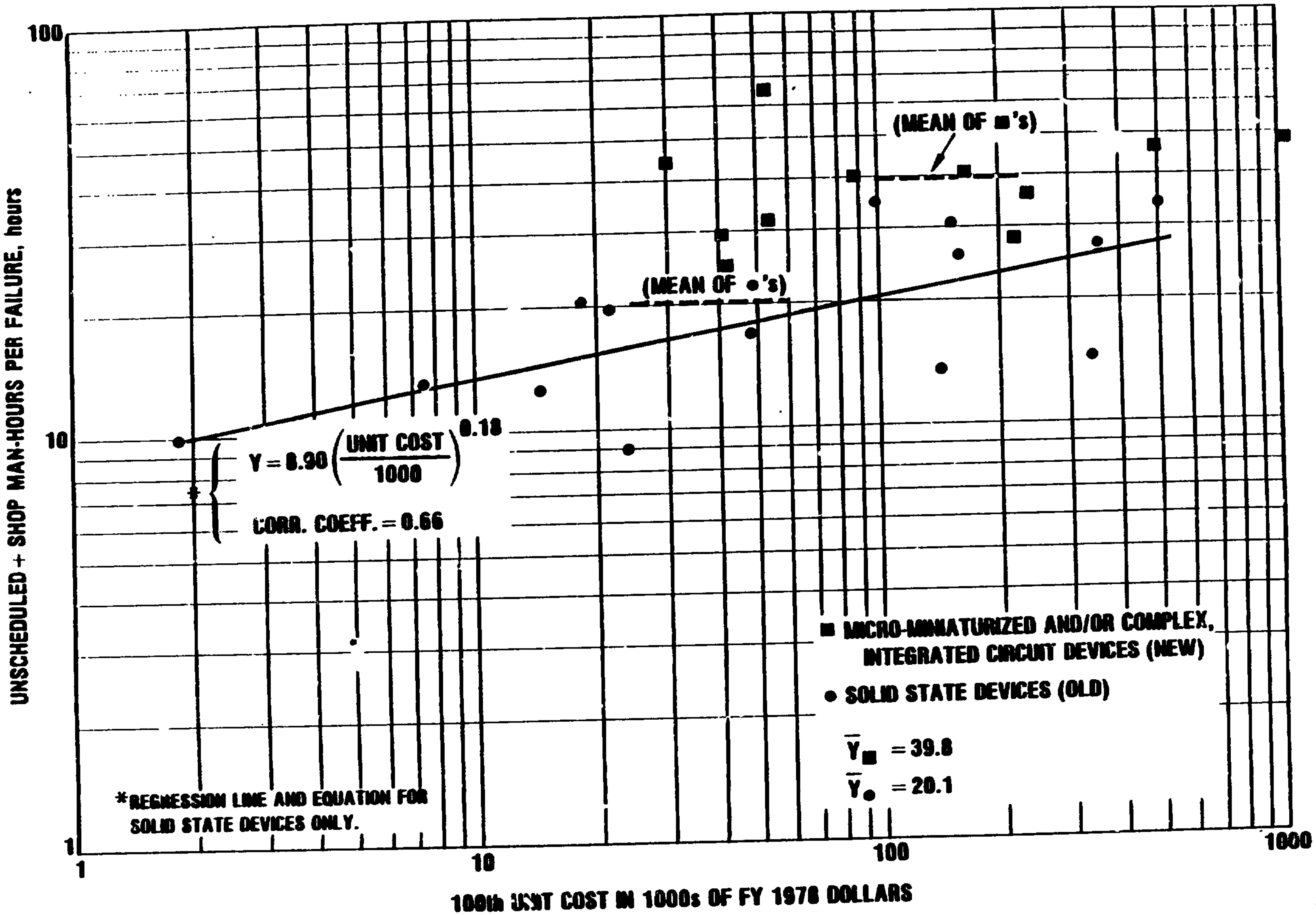

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Figure 4. $\frac{\text{UNSCHEDULED + SHOP MAN-HOURS}}{\text{FAILURES}}$ VERSUS UNIT COST FOR SELECTED AVIONIC EQUIPMENTS

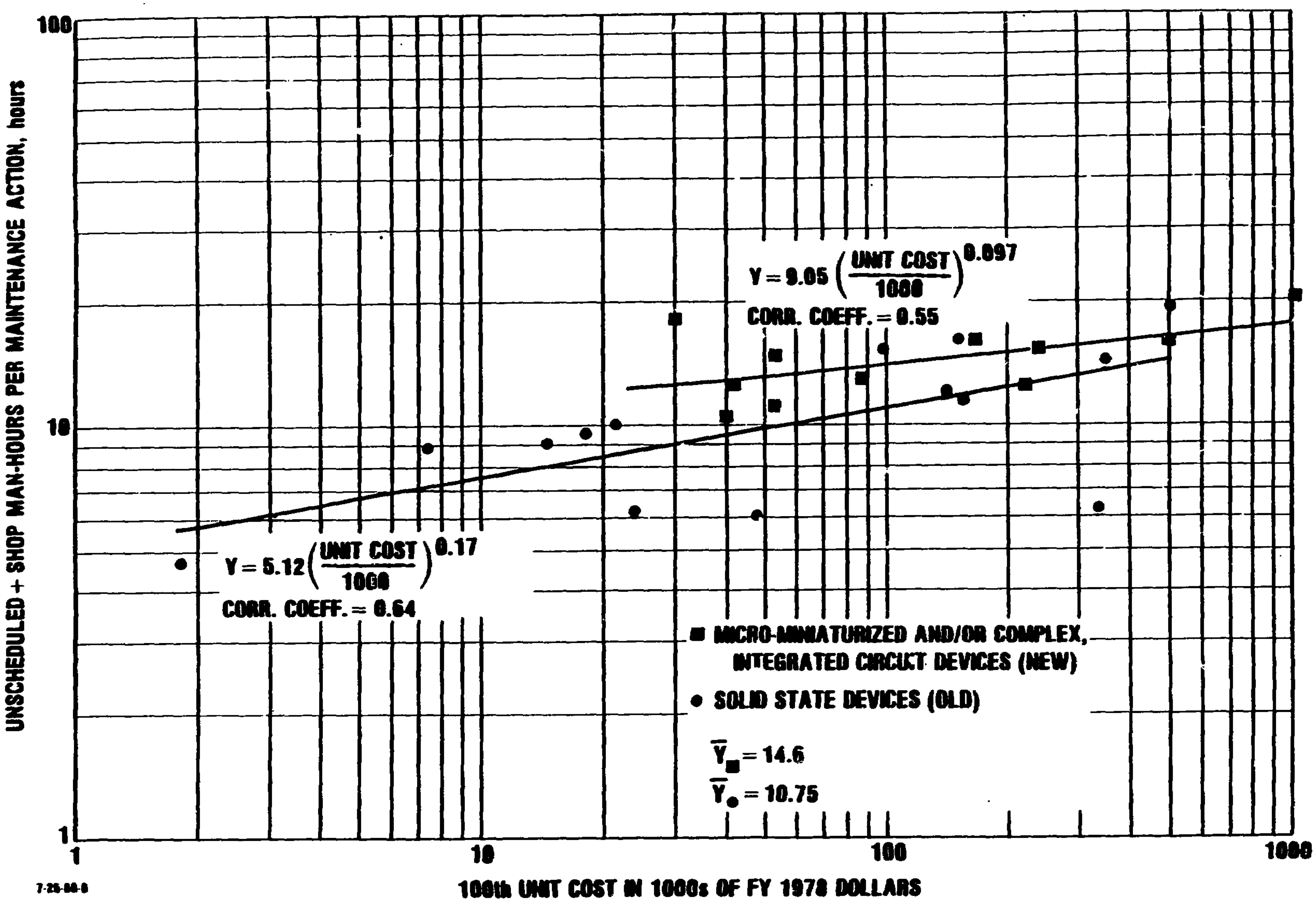

Figure 5. $\frac{\text{UNSCHEDULED + SHOP MAN-HOURS}}{\text{MAINTENANCE ACTION}}$ VERSUS UNIT COST FOR SELECTED AVIONIC EQUIPMENTS

Finally, correlation of maintenance man-hours per operating hour and unit cost were prepared. Table 3 presents the data used to develop the maintenance man-hours per operating hour for each piece of equipment. The same man-hours were used as in the previous discussion. The data points and the equations are plotted in Figure 6. The correlation coefficients are much better than those of the previous regressions using man-hours per failure or man-hours per maintenance action. Note that the curve described by the micro-miniaturized (newer technology) points lies below the curve described by the solid-state devices (older technology) points. It has already been shown that although the newer-technology equipments fail less frequently, they require more man-hours per failure to repair. The results of this maintenance-man-hour-per-operating-hour analysis indicate that the improvement in reliability of the newer-technology equipments more that offsets the additional man-hours needed to repair failures at the organizational and intermediate levels of maintenance.[1]

V. SUMMARY

The results of these reliability and maintainability analyses can be summarized as follows:

- Field reliability (measured by MTBF and MTBMA) varies inversely with unit cost for avionic equipments of the same technology level.
- Given two avionic devices having the same unit cost, one typified by the newer micro-miniaturized/complex integrated circuit technology, the other by the previous generation solid-state technology:

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[1]This finding does not imply that all maintainability problems are offset. The need for additional maintenance man-hours per failure could increase aircraft turnaround times or, alternatively, increase maintenance skill requirements.

Table 3. OPERATING HOURS, MAINTENANCE MAN-HOURS AND COST DATA FOR SELECTED AVIONIC EQUIPMENTS

Equipment No.	Type[a]	No. of Operating Hours	Man-Hours			Unscheduled + Shop M-Hrs. / Operating Hrs.	Unit Cost (FY 78 $) 100th Unit
			Unscheduled	Shop	Unscheduled + Shop		
1	SSD	18,524	172	55	227	0.0123	1,800
2	SSD	145,811	11,546	15,746	27,292	0.1872	7,400
3	SSD	18,524	3,142	4,056	7,198	0.3886	14,400
4	SSD	21,738	6,245	2,759	9,004	0.4142	18,100
5	SSD	18,542	4,648	2,205	6,853	0.3700	21,500
6	SSD	139,288	12,018	10,227	22,245	0.1597	23,800
7	SSD	6,523	1,115	422	1,537	0.2356	47,900
8	SSD	6,763	1,669	2,302	3,971	0.5882	97,600
9	SSD	3,286	908	599	1,507	0.4586	140,800
10	SSD	18,524	5,149	4,831	9,980	0.5388	152,000
11	SSD	18,524	8,724	4,932	13,656	0.7372	156,400
12	SSD	77,448	104,444	67,060	171,504	2.2144	338,600
13	SSD	18,524	20,312	16,186	36,498	1.9703	350,700
14	SSD	18,524	18,486	27,317	45,803	2.4726	498,200
1	MM	52,309	4,272	7,176	11,448	0.2189	30,000
2	MM	52,309	2,392	2,135	4,527	0.0865	40,900
3	MM	52,309	2,147	3,181	5,328	0.1019	42,200
4	MM	52,309	1,548	3,404	4,952	0.0947	53,000
5	MM	52,309	1,705	2,732	4,437	0.0848	53,700
6	MM	52,309	10,428	15,779	26,207	0.5010	87,300
7	MM	52,309	8,899	17,375	26,274	0.5023	164,600
8	MM	18,524	3,469	4,752	8,221	0.4438	219,800
9	MM	52,309	7,482	14,364	21,846	0.4176	235,000
10	MM	52,309	3,283	12,318	15,601	0.2982	490,000
11	MM	52,309	45,471	77,714	123,185	2.3549	1,015,900

[a]SSD = Solid State Devices
MM = Micro-Miniaturized and/or Complex, Integrated Circuit Devices

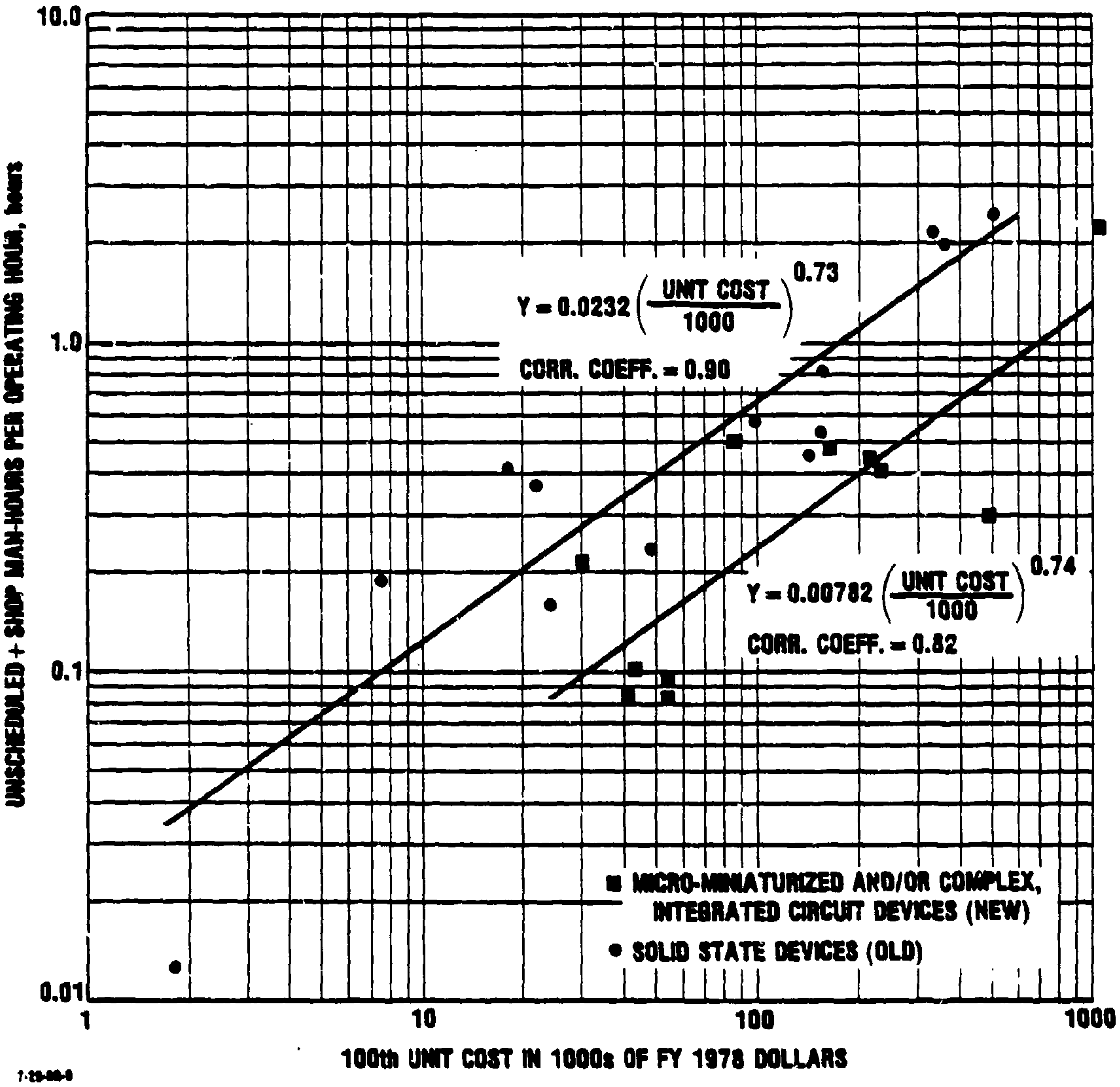

Figure 6. $\frac{\text{UNSCHEDULED + SHOP MAN-HOURS}}{\text{OPERATING HOURS}}$ VERSUS UNIT COST FOR SELECTED AVIONIC EQUIPMENTS

- The field reliability of the equipment characterized by the newer technology would exceed that of the older technology by a factor of five....however,
- Given a failure, the equipment incorporating the newer technology may consume twice as many man-hours to repair at the organizational and intermediate levels.
- Maintenance man-hours expended per operating hour at the organizational and intermediate levels on avionics typified by the newer technology approximates 40 percent of the man-hours devoted to avionics incorporating the older technology.

Regarding the results of the foregoing reliability analyses, we fully expect that the quantitative values (e.g., the equations and correlation coefficients) would change somewhat with enlargement and refinement of the data base. We believe, however, that the trends and relationships, as stated qualitatively in our findings, are unmistakable.

The results of our maintainability analyses are less satisfying. Although indicative of the organizational and intermediate levels of maintenance, consideration of unscheduled depot-level maintenance is needed to attain more complete understanding.

VI. TEST MTBF VS. FIELD MTBF

In the course of our study of the avionic system approaching a DSARC milestone, some DoD officials concerned with the system frequently referred to an MTBF value given in the System Segment Specification, which referenced the applicable reliability test MIL STD, as expected field MTBF. In fact, that MIL STD [5] specifies that the MTBF value is "...for the purpose of establishing accept/reject criteria and shall not be used for projection of equipment MTBF."

The fallacy [illegible]ing the results of demonstration, development, or qualification tests as representative of expected field reliability is exemplified by the Failure Tree in Figure 7. The reliability demonstrated for a similar avionic system by the FSD contractor is used as the example. Note that the 325-hour

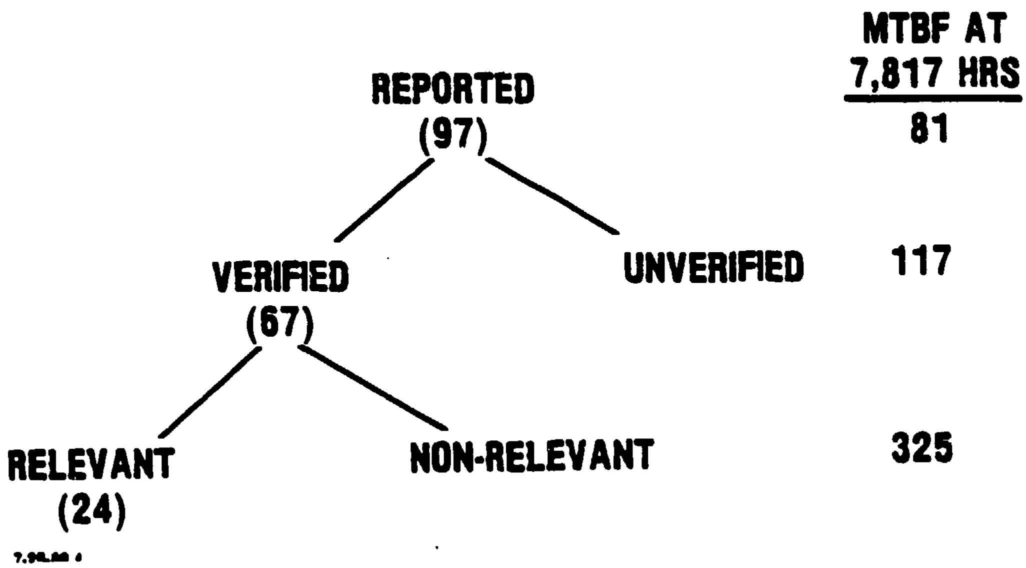

Figure 7. FAILURE TREE

MTBF in the column on the right is based on relevant failures;[1] and relevant failures, by contractual agreement, were the basis for determination of the contractor's compliance with reliability specifications. Actually, 97 failures were initially reported as equipment failures, of which 67 were verified as equipment failures. Of the 67, only 24 were eventually classified as relevant, yielding by contractual definition, an MTBF of 325 hours.

In deployed operational units, however, discrimination between relevant and non-relevant failures is immaterial. Each perceived (i.e., "reported") failure generates a maintenance action and each verified failure frequently generates spares requirements and additional maintenance effort. With reference to the example in Figure 7, the D056 Log report would have shown a 117-hour MTBF; about one-third of the 325-hour MTBF resulting from contractual definition. Obviously, the indiscriminate use of the acronym "MTBF" can be grossly misleading, especially in planning for O&S resources for new avionic systems.

[1]Testing was conducted consistent with MIL-STD-781B, which defined relevant failures as those attributable to the contractor's performance (e.g., design, workmanship and premature part failure). Discrimination between relevant and non-relevant failures, however, are subject to negotiation.

REFERENCES

[1] Air Force Audit Agency, Department of the Air Force, Summary Report of Audit, *Impact of New Management Concepts on Support and Maintainability of Avionic Equipment* (87381), 23 March 1979.

[2] *Maintenance Actions, Manhours and Aborts by Work Unit Code for Various Aircraft*, AFLC-PCN DC56B5006, RCS: Log-MMO (AR) 7170, August 1979-January 1980.

[3] Air Force Logistic Command, *Maintenance Actions, Manhours and Aborts by Work Unit Code*, PCN: D056B5006, 1 July 1976.

[4] Headquarters, Air Force Logistics Command (AFLC/LOEP), Wright-Patterson AFB, Ohio.

[5] *MIL-STD-781C, Military Standard, Reliability Design Qualification and Production Acceptance Tests; Exponential Distribution*, AMSC No. 22333, Department of Defense, 21 October 1977.

APPENDIX

REGRESSION ANALYSIS METHODOLOGY

REGRESSION ANALYSIS METHODOLOGY

In simple linear correlation the correlation coefficient (r) is a parameter commonly applied to test the "goodness of fit" of the data points used to generate a straight (regression) line by the method of least squares. A correlation coefficient of 1 (i.e., perfect correlation) would mean that all points used to describe the regression line fell on the line, and that estimates made from the line (or its equation) would be without error. Although "goodness of fit" should not be confused with causality, normally the closer r is to 1, the higher the confidence that can be placed in estimates that fall within the range of the data. The square of the correlation coefficient, named the index (or coefficient) of determination, indicates the proportion of variation in the dependent variable (Y) that can be explained in terms of the independent variable (X).

Regression analyses were performed on historical cost, reliability and maintainability data to determine if relationships between cost and the reliability and maintainability variables could be developed. The regression analyses were performed on the General Electric (GE) Time Sharing System, using the standard GE program CURFT$. The program executes "...a regression analysis on bivariate data, calculating regression coefficients and an index of determination for each of six curve types."[1]

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[1] *User's Guide Statistical and Mathematical Programs*, General Electric Report 5700.01, October 1971.

It was decided to utilize throughout this Paper the one curve type of the six in the G.E. program that yielded the best fit most often. Outputs of the G.E. program were examined and, through ranking the values of the correlation coefficients for the six curve types for all of the regressions, the power form ($Y=AX^b$) was indicated as the choice. The power form is a non-linear equation, however, and the G.E. program transforms the input data, as necessary, so that the equation derived from those data is expressed in linear form to enable linear correlation. To obviate the effect of data transformation, we examined the values of the means and the standard deviations[1] of the differences between the actual values of the dependent variables and the values calculated for those variables from the regression equations generated by the G.E. program. The resulting values of standard deviation were then ranked, as before, to select the most representative curve type. Again, the power form was indicated as the choice; accordingly, it was used throughout this Paper. The reader should be aware that the regression equations, correlation coefficients, and figures in the main text reflect the data transformation performed by the G.E. program. This fact does not diminish the validity of the analyses.

[1]Standard deviations were computed using the unbiased estimator; that is, the sum of the squared deviations was divided by (n-1) rather than (n).